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Opening and Closure of a Marginal Southern California Lagoon Inlet

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ABSTRACT: Over the past 50 yr, direct observations of the inlet status (open or closed) of San Dieguito Lagoon, a typical southern California lagoon located in Del Mar, California, have shown that river flooding is the major natural determinant of inlet conditions on time scales longer than a few years. River flooding is strongly dependent on rainfall in the San Dieguito River watershed and on the influences of two water storage reservoirs in the area. Rainfall fluctuates on yearly and longer time scales and undergoes cycles of wet and dry periods. Over short time periods, ranging from a few months to several years, inlet status is primarily determined by the available tidal prism and littoral sand transport. Recognition of these factors is crucial in order to correctly evaluate the probability that a small lagoon will remain open naturally. A probability approach is essential because the variables controlling inlet conditions are random in nature. The results of our study show that the inlet will remain open naturally 34% of the time. The tendency to remain open is vastly smaller during years of dry weather (12%) versus times of above-average rainfall (66%).

Introduction

The objective of this paper is to estimate the probability, or fraction of time, that a marginally stable southern California lagoon inlet will remain open naturally to the ocean. Evaluation of the probability that marginal lagoons will remain open naturally is needed to assess enhancement and restoration efforts. Engineering design of inlet stabilization and maintenance depends on the correct assessment of the factors controlling the inlet configuration.

This paper addresses a specific lagoon, but one which is typical of many located along the southern California coast. The results of this study apply to small estuarine lagoons worldwide where weather has distinct wet and dry episodes, in particular, to many lagoons along the coast of Baja California, Mexico, that are in essentially pristine condition. A large number of lagoons on the Pacific coast are located at river mouths (Johnson 1973). During floods their inlets flush and open. For those lagoons heavily influenced by river flow, the importance, and even episodic dominance, of fluvial processes has only recently been recognized (Escoffier and Walton 1979; Kjerfve and Magill 1989; Webb et al. 1991).

Studies on the stability of lagoon inlets with entrances across sandy beaches have emphasized the roles and relative importance of tidal prism versus longshore sand transport potential (O'Brien 1931; Inman and Frautschy 1965; O'Brien and Dean 1972; Escoffier 1977; Bruun 1978). Goodwin and Williams (1992) applied the results of these studies to California wetlands. The available stability criteria can qualitatively provide some useful insight into the length of time a lagoon inlet may remain open in the face of littoral processes acting to close the inlet. However, they fail to reasonably account for the important effect of episodic flushing due to floods.

All previous work predicting inlet closure has been based on short-term observations and using deterministic approaches. The present study realizes the importance of adapting a probability approach because the processes controlling the long-term condition of the inlet are random in nature.

Data used for the present study consists of a time history from 1946 to 1994 of inlet status (open or closed) compiled from aerial photographs, lifeguard logs, beach studies by Flick and Waldorf (1984), Audubon Society bird surveys, and literature review; monthly rainfall data from 1860 to 1994; and dam spillover data and resulting river flow for the period 1920 to 1994.

San Dieguito Lagoon is a 57-ha (140-acre) wetland located on the northern edge of the city of Del Mar in San Diego County, California. The lagoon forms the lower part of the San Dieguito River Valley (Mudie et al. 1976). The lagoon can be divided into four main sections: the inlet, and the West, North, and South channels (Fig. 1). The South Channel extends southeastward and consists of 36 ha (90 acres) of mud flats and tidal basin, representing the largest portion of the lagoon. The South Channel was restored to a fully functional

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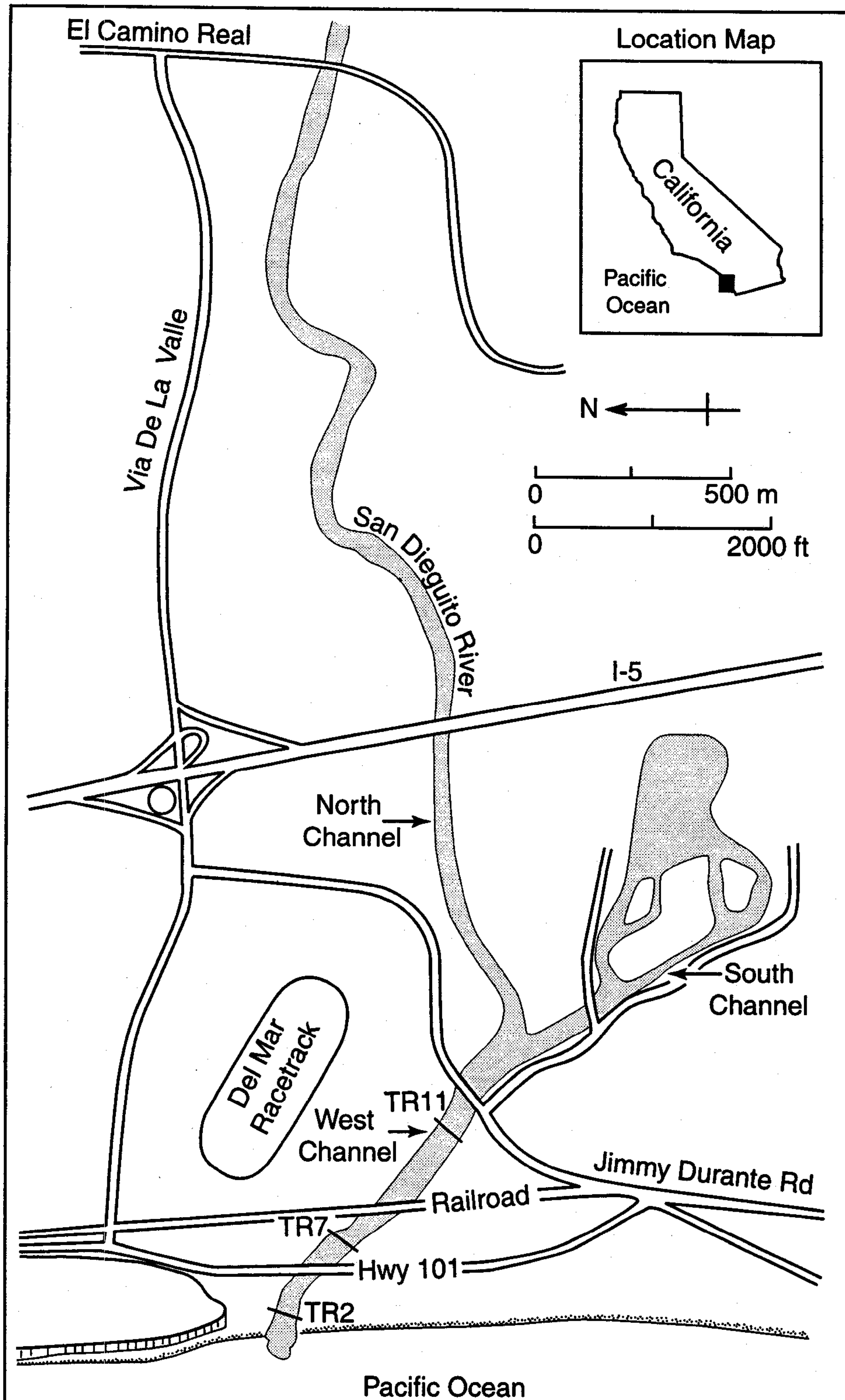

Fig. 1. Map of San Dieguito Lagoon showing the major channels, roadways, and bridges and the location of inlet channel cross-sections TR2, TR7, and TR11. Lake Hodges Dam is located 14 km east of El Camino Real.

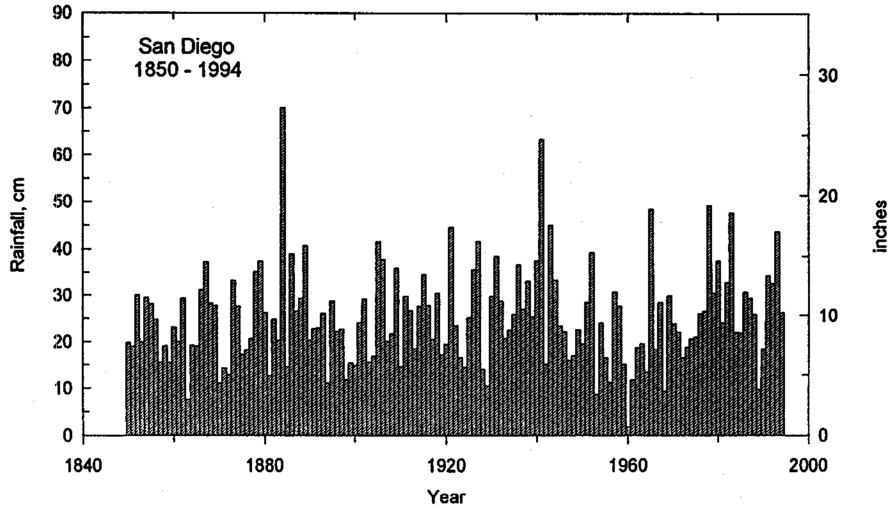

Fig. 2. Yearly rainfall in San Diego, California 1850–1994.

wetland in 1983 (California State Coastal Conservancy 1989). The San Dieguito River drainage basin has an area of 900 km^2, of which 120 km^2 are below Lake Hodges Dam, which was built in 1919. Lake Sutherland Dam, built in 1953, controls only the upper 135 km^2 of the watershed.

Rainfall and Runoff Statistics

Rainfall

Rainfall in San Diego County is closely associated with storms that approach from either the northwest, west, or southwest. Rainfall amounts vary from one local geographic area to another during each storm. Rainfall increases rapidly with distance inland, and decreases slightly along the coast from north to south. However, the rainfall patterns are remarkably similar, so that time series of average rainfall differ mainly in magnitude from place to place but are similar in trends. For example, rainfall data from a station near San Dieguito Lagoon (Del Mar Fire Station), collected since 1965 indicate annual rainfall patterns and magnitude nearly identical to those recorded at Lindbergh Field, 20 km south of San Dieguito Lagoon.

Rainfall data from the San Dieguito River watershed are only available for the past few decades. However, records in San Diego (Lindbergh Field) begin in 1850. The rainfall data from Lindbergh Field is taken as being representative of rainfall in the San Dieguito River watershed for the purpose of calculating the probability of wet and dry periods. Using the longer term record increases our confidence in these statistics.

Figure 2 shows the yearly rainfall at San Diego from 1850 to 1994. Figure 3 shows the cumulative residual rainfall, r_t, calculated from the yearly data for any year, t, according to the equation:

$$r_t = \sum_{i=t_0}^{i=t} (r_i - \bar{r})$$

where $\bar{r}$ is the mean rainfall over the entire record and r_i is the rainfall in year i.

Unlike the actual rainfall (which can only be nonnegative), the cumulative residual can be positive or negative, since it represents the running departure from the mean as a function of time. The cumulative residual will increase during times of above-average rainfall and decrease during periods of below-average rainfall. The cumulative residual rainfall is an excellent way to identify long-term patterns of wet and dry years. Years with below-average seasonal rainfall result in a decreasing trend in the cumulative residual curve, and are defined as "dry years," while those with above-average values produce an increasing trend, and are "wet years." Variations in cumulative residual rainfall reveal climate fluctuations that are large compared to the typical seasonal cycle in rainfall in San Diego (about 25 cm), and which lead to wet and dry periods that can last for decades (Fig. 3).

The time period from 1920 to 1945 was generally wet, with heavy rain during the winter of 1940–1941, while the period from 1946 to 1977 was largely dry. Annual rainfall during the 17 yr from 1978 to 1994 averaged 28.7 cm. This is more than 14% above normal, although some dry years (1981, 1984, 1989) occurred in this generally wet interval. The year 1978 marked the end of the 32-yr dry period that started in 1946. The average rainfall during this period was only 21.6 cm, even

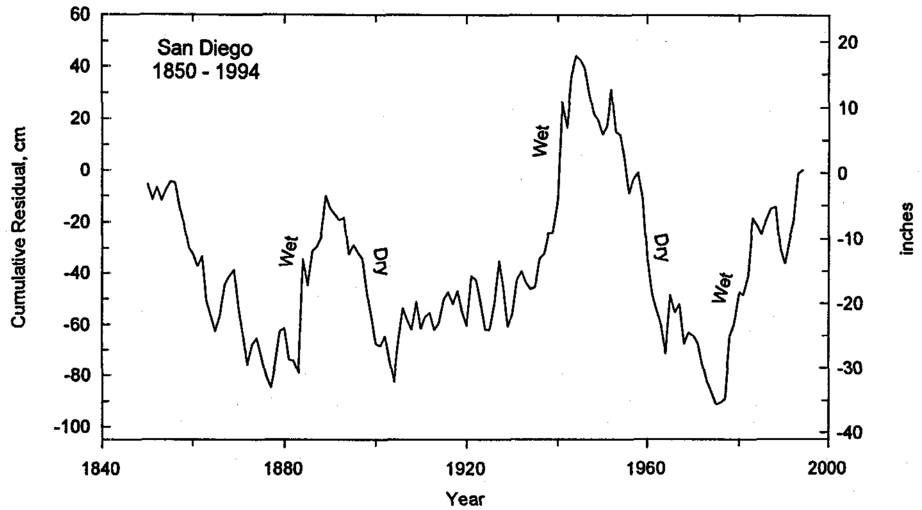

Fig. 3. Cumulative residual rainfall in San Diego, California illustrating the wet and dry periods.

though it included several years of much higher than average rainfall (over 46 cm in 1951–1952 and over 38 cm in 1965–1966).

Short-term wet periods are imbedded in longer term dry periods and vice-versa (Fig. 3). This makes exact definition of their start and end times dependent on the time scale chosen or period of record available for analysis. To avoid this problem, the probability distribution of rainfall can be used to determine the relative abundances of wet and dry periods. The cumulative probability distribution for rainfall is shown in Fig. 4. The climate in San Diego is dry (rainfall below average) about 60% (0.6) of the time, while it is wet (above-average rainfall) about the remaining 40% (0.4) of the time.

Lake Hodges Dam Overflows

Lake Hodges Dam is located 14 km east of El Camino Real (Fig. 1). Spillover data from the dam are shown in Fig. 5, and compare well with the measured river flow at El Camino Real bridge. From 1919 to 1994, the dam spilled-over 27 times. Sixteen of these spills (59%) occurred before 1947. Annual Lake Hodges Dam spillover volumes vary from near zero to a high of about 300 million m^3 in 1980. Beginning in 1978, the dam spilled over for 7 consecutive years, and for up to 7 mo yr^{-1}. For 25 yr, between 1953 and 1978, there had been no spills at all, and the reservoir was well below capacity much of that time. During the 32-yr dry period from 1946 to 1977, there was only one small spill, in 1952 (Fig. 5).

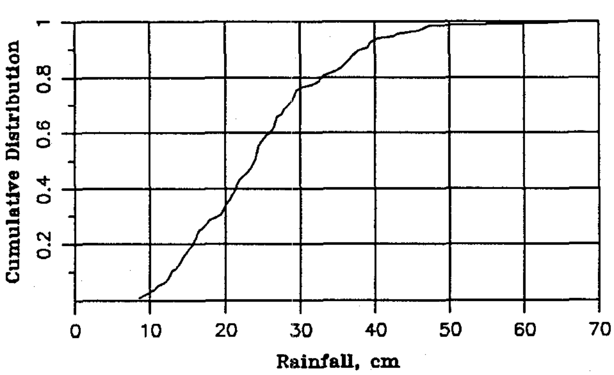

Fig. 4. Cumulative probability distribution of rainfall in San Diego, California.

Inlet Open or Closed Status

The dynamics of small, shallow lagoon inlets are highly complex the world over (Bruun 1978; Inman and Dolan 1989; Kjerfve and Magill 1989), and those in southern California are no exception. Lagoon hydrodynamic behavior depends on channel bottom topography, which changes rapidly in response to river floods, tides, and wave-driven sand transport.

The typical inlet opening and closing sequence observed at San Dieguito Lagoon begins when a major river flood scours the lagoon and inlet channels. Such a sequence is illustrated in Fig. 6, which shows channel cross sections at traverses TR2, TR7, and TR11 respectively (see Fig. 1). The cross-sectional area of the inlet channel at TR2, TR7, and TR11 increased sharply as a result of the January and February 1993 flood flows (Fig. 5), reaching depths of about −2 m, −2.5 m, and −2 m below mean sea level (MSL), respectively. This is below the equilibrium depth that can be sustained by the maximum available tidal prism.

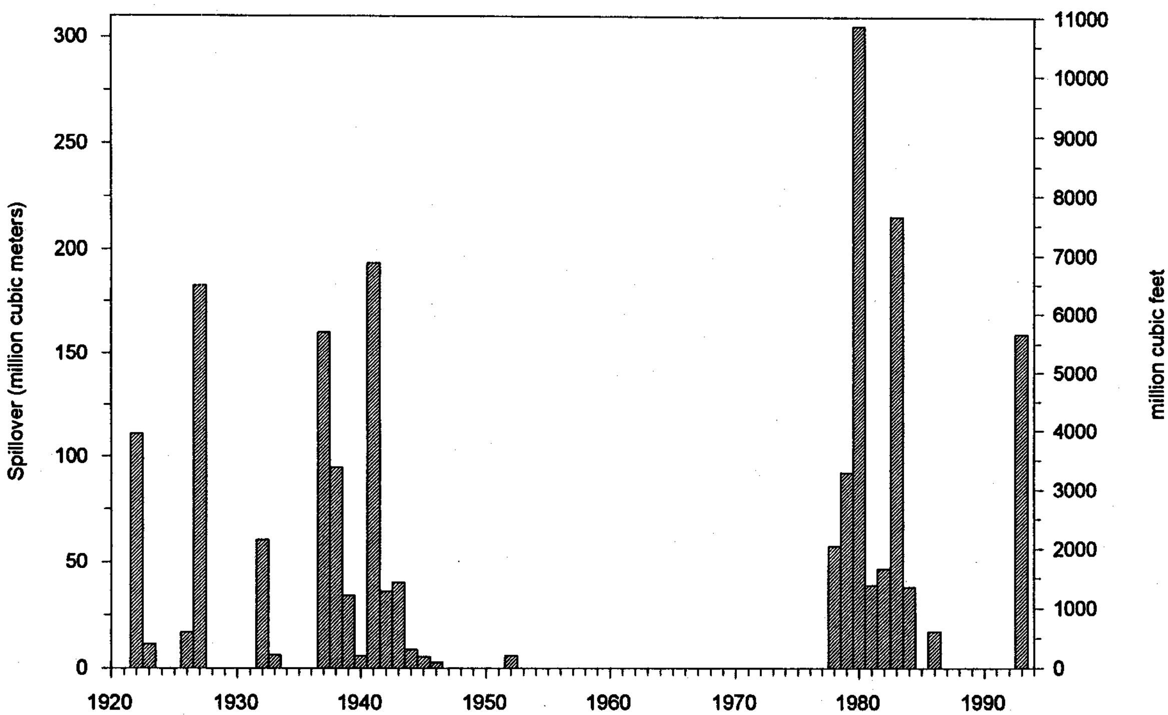

Fig. 5. Lake Hodges Dam spillover, 1920–1994.

Littoral sand, washed into the inlet by tidal flow and wave surges, rapidly filled the entrance and exterior portions of the channels. By December 1993 the inlet at TR2 (Fig. 6) had filled with sand to a near-equilibrium depth of about −1 m (MSL). It had also migrated across the beach about 200 m to the north as a result of the prevailing wave pressure during this interval. Meanwhile, the inlet at TR7 had also filled with littoral sand to about the same depth, as shown in Fig. 6. The channel could not migrate at this location because it has been stabilized by bridge abutments and training walls. At TR11, located about 0.6 km inland from the beach (Fig. 1), the channel remained essentially unchanged between April and November 1993, as shown in Fig. 6. This confirms the observation that the exterior channels fill with littoral sand (not river-borne sand) over a period of several months, some time before it reaches the interior of the lagoon. The interior channels slowly fill over a period of 2–5 yr, decreasing the tidal prism and eventually leading to a relatively sudden closure of the lagoon.

When there are no floods, and river flow is insufficient to fill Lake Hodges and spill over the dam, the lagoon remains closed. Exceptions may occur during unusually high tide events, when large waves temporarily overtop or breach the beach berm, during periods of heavy rains, or when the lagoon has been artificially opened. How long the inlet stays open depends upon the condition of the interior lagoon channels. If the lagoon channels are shallow and narrow, the inlet will remain open for only a period of days or weeks, and will close rapidly. If the interior channels are still relatively free of sand, tidal flushing will re-establish the inlet and the lagoon will remain open. This suggests that as long as sufficiently strong river flow occurs every 3 yr to 5 yr, San Dieguito Lagoon will remain open indefinitely, or at least with minimal maintenance.

The time history of San Dieguito lagoon inlet's open-or-closed status has been compiled. Figure 7 shows the available data on a monthly basis from 1946 to 1977, a period of irregular observations obtained mainly from aerial photos and written documents. Figure 8 shows the information that is available between 1978 and 1994.

The most striking feature of Fig. 7 is that it suggests that the lagoon inlet was closed most of the time from 1946 to 1977. As noted, this was also an interval when the rainfall was below average, thus constituting a dry period. In clear contrast, Fig. 8 shows the inlet was open most of the time from 1978 to 1994. As noted, the years from 1978 to the present are a wet period.

Figures 7 and 8 clearly indicate that there are long-term and short-term patterns of lagoon en-

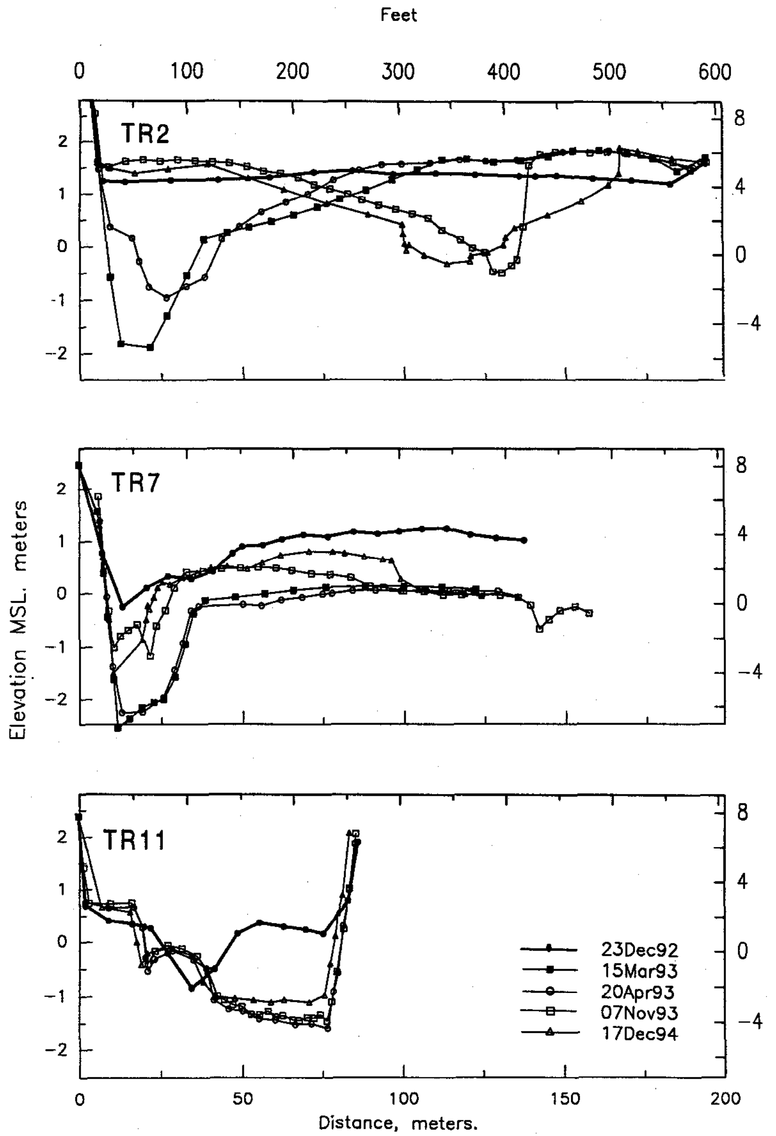

Fig. 6. San Dieguito Lagoon inlet channel cross sections at TR2, TR7, and TR11.

trance closure. Based upon recent measurements of the San Dieguito inlet, it appears that short-term closures occurring during years when the lagoon is mostly open result from short periods of rapid sand deposition in the inlet. These closures are associated with intense wave action and the resulting high rates of sand transport across or along the beach. As an example, after the January and February 1993 floods (Fig. 5), the lagoon inlet and channels were deepened to about −2 m and remained relatively deep until December 6, 1994, when a large wave storm of 3 m significant wave height suddenly closed the lagoon inlet. Since the lagoon channels were still deep, high tides on December 10, 1996, opened the lagoon 4 d after it closed. As sediment gradually encroaches into the lagoon a number of short-term openings and closings may occur during the months or years before the longer term closure is complete.

In contrast, long-term closures appear to result from extensive sedimentation in the inlet and West Channel near the beach, as well as in the North Channel, during extended periods of low river flow, as shown in Fig. 6. A long-term inlet closure, or series of closures, dominated San Dieguito Lagoon starting in 1946 and continuing to the late 1970s (Fig. 7). After the 1983 flood, sand accumulations became significant over 5 yr. As a result, the lagoon closed in November 1989 and stayed closed until the beginning of 1992. A series of sev-

MONTH	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77
January														C											C			c	I			C
February													C	C								C		C		C		C		C		
March														C										C	C			c		c	O	C
April								C	C					C									C	C	C		O			O		
May														C				C							C		C	I				
June									C			C	C	C				C	C		C			C				C			C	
July								C			C		C	C					C	C				C						C		
August													C	C					C			C					C	C		C	C	
September	C												C	C												C		I				
October						C							C							C		C					c	I			C	
November							C						C											C			C	I	C			
December													C							O					c		C	O				c
Annual data from literature*	C							C	C	C	C	C	C	C	C	C	C	C	C	C	O	C	C	C	C	C	C	C	C	C		

* General Statement

O = Open inlet
C = Closed inlet
c = Artificially opened inlet
I = Intermittent inlet

Fig. 7. Inlet status (open or closed) at San Dieguito Lagoon, 1946–1977.

eral short openings and closures followed, as well as a longer closure lasting 9 mo, through the end of 1992 (Fig. 8).

These patterns of opening and closure are associated with southern California lagoon inlets (with areas on the order of 1 km²) and don't necessarily apply to large lagoon systems (with areas on the order of 10 km²) such as those of the United States east coast, Europe, or North Africa. For large lagoon systems, different processes may take place and control inlet opening or closure status.

The Probability Approach

The relation used to compute the overall probability P_o of an open inlet over two different periods, one wet and one dry, is a form of Bayes' Equation (Bayes 1763):

$$P_o = P_{ow} N_w + P_{od} N_d \tag{1}$$

where P_{ow} is the probability of an open state of the inlet in wet periods, and P_{od} is the probability of an open state in dry periods, and N_w and N_d represent respectively the probabilities of wet and dry

MONTH	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
January	O	O	O	c	c	O	O	O	O	O	I	O	c	C	O	O	O
February	O	O	O	O	c	O	O	O	O	O	O	O	c	C	O	O	O
March	O	O	O	O	O	O	O	O	O	c	O	C	I	c	I	O	O
April	O	O	O	O	O	O	C	O	O	I	I	C	c		I	O	O
May	O	O	O	C	O			O	O	c	O	C			C	O	O
June	O	O	O	C	O	O	C	O	O	O	O	I	C	C	C	O	O
July	O	O	O	C	O	O		O	O	O	O	C	C	C	C	O	O
August	O		O	C	O	O	O	O	O	O	O	O	C		C	O	O
September		O			O	O	O	O	O	O	O	c	C	C	C	O	O
October		C	C	C	O	O		O	O	O	I	O	C	C	C	O	O
November		I	C	C	O	I	c	O	O	I	I	C	C		C	O	O
December	O	c	C	c	O	O	O	O	O	I	O	C	C	C	C	I	I
Annual data from literature*																	

* General Statement

O = Open inlet
C = Closed inlet
c = Artificially opened inlet
I = Intermittent inlet

Fig. 8. Inlet status (open or closed) at San Dieguito Lagoon, 1978–1994.

years. If $P_c = 1 - P_o$ represents the probability of a closed inlet over wet and dry periods, then the following two constraining conditions:

$$P_{ow} + P_{cw} = 1$$

and

$$P_{od} + P_{cd} = 1$$

must be satisfied in order for Eq. (1) to be a properly posed probability equation. Here P_{cw} and P_{cd} are the probabilities that the inlet is closed during wet and dry periods, respectively. Equation (1) requires estimates for four parameters: N_w, N_d, P_{ow}, and P_{od}. N_w and N_d can be calculated from Fig. 4 ($N_w = 0.40$, $N_d = 0.60$).

P_{ow}, the probability that the inlet will remain open during a wet period, can be computed from the data in Fig. 8, which shows the state of the inlet during each month from 1978 to 1994. These data are derived from regular monthly observations and reports with few gaps. The inlet was observed to be open during 121 of 189 mo. Therefore, $P_{ow} = 121/189 = 0.64$.

P_{od}, the probability that the inlet will remain open during a dry period, can be computed from the data shown in Fig. 7, covering the dry period from 1946 to 1977. These data are derived from photographs and reports that refer to the state of the inlet on a particular day only, and are often separated by long gaps. Assuming the observations to be independent (drawn randomly), and assigning equal weight to each, gives the value, $P_{od} = 0.06$. Substituting these values of N_w, N_d, P_{ow}, and P_{od} into Eq. (1) gives $P_o = 0.29$.

The acreage of the lagoon was fairly stable after 1941, when the major fillings for the fairgrounds, airport, and sewage ponds were completed. However, at the end of 1983, the lagoon area was increased by 32 ha (80 acres) due to excavations in the South Channel region by the California Department of Fish and Game. In order to evaluate the change in the predicted value of P_o because of this change in lagoon area, one can assume that the increased tidal prism resulting from this restoration affects the short time-scale behavior of the inlet, keeping it open for a longer period following large floods.

P_{od}, calculated above for the period 1946–1977, can be adjusted to account for the change in tidal prism because of the South Channel restoration. Inspection of Fig. 5 indicates there was only one spillover from Lake Hodges Dam between 1946 and 1977, and this occurred in 1952. The history shown in Fig. 8 indicates that the duration assigned to each open period should be between 1 yr and 4 yr. Therefore, in order to re-compute P_{od} for the time period 1946–1977, adjusting for the effects of increased tidal prism due to South Channel enhancement in 1983, we assume that the inlet would have remained open for another 2 yr (i.e., 24 mo) following the flood of 1952, instead of closing immediately. This estimate is based on the average value for the time period the lagoon remained open during similar flood intensities.

Since $P_{od} = 0.06$, the lagoon was open for 23 mo over the 32-yr (384-mo) dry period. Assuming that the inlet would have remained open for an additional 24 mo due to the 1952 flood, the inlet would have been open for a total of 47 mo during that period. This gives $P_{od} = 47/384 = 0.12$.

Similarly, P_{ow} can be re-estimated for 1984–1994 (the period when the South Channel enhancement existed) from Fig. 8. This gives $P_{ow} = 0.66$, which is essentially the same value as we already derived for 1978–1994. Substituting the recalculated values of N_w, N_d, P_{ow}, and P_{od} into Eq. (1) gives $P_o = 0.34$.

Conclusions

River flooding is the major natural determinant of whether the San Dieguito Lagoon inlet will be open or closed on time scales longer than a few years. Over short time periods ranging from a few months to several years, inlet status is controlled by lagoon channel topography, available tidal prism, and beach sand transport (along and cross shore).

The approach used in this study is based on historical observations of the open and closed status of San Dieguito Lagoon, together with observations of rainfall. These observations are interpreted in light of the understanding of lagoon processes achieved from detailed hydrological studies conducted from 1992 through 1995 and from available historical information. The data were used as input to the probability model, which provides the most convincing basis to predict the fraction of time the lagoon will be open in the future.

The calculations of inlet status probability made here aim to overcome the problem of selecting time periods not representative of the long-term probability of inlet opening or closure. Depending on which nonrepresentative time period is used, the predicted value of P_o can vary from 0.12 (for a dry interval, when $P_d = 1$) to 0.66 (for a wet interval, when $P_w = 1$).

Historically, the inlet has been open only about one-third of the time. Since we can only assume that future climate statistics will resemble those of the past, the only way to reasonably estimate P_o is to base the estimate on the most complete probability analysis of previous occurrences.

Acknowledgments

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